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Title no. 110-S16

Lap Splices of Bars in Bundles

by John Cairns

European (EC2) and ACI 318-08 design code rules for lap splices of reinforcing bars within a bundle differ markedly—the former permits the same or shorter lap-splice lengths with respect to splices of individual bars, while the latter requires longer laps. This paper reports an investigation into the performance of lap splices of individual bars within a bundle of two or three. The results show that the bond strength of individual bars is not reduced on account of their forming part of a bundle (contrary to the provisions of ACI 318-08). Staggered laps were found to be weaker but fail in a less brittle manner when splices are staggered longitudinally as compared to equivalent laps, where all bars are spliced at the same section whether or not bars were bundled. Therefore, the outcome raises the question of the validity of reductions permitted by both the ACI 318-08 and European (EC2) codes, where only a portion of the bars is lap-spliced at a section. It is recommended that further investigation of the influence of the proportion of bars lapped at a section on splice performance be undertaken.

Keywords: bond strength; brittleness; bundles; lap splices.

INTRODUCTION

In situations where reinforcement is congested, it may be advantageous to place bars in bundles of two, three, or four instead of fixing individual bars at equal spacing.¹ Bundles permit flexibility in detailing where availability of larger bars is restricted and ease manual handling on site. Bundling of bars allows for increased clear spacing, facilitating compaction of concrete between bundles. In comparison with reinforcement in layers, bundles are more efficient in maintaining the effective depth of longitudinal reinforcement. Bundles may permit cross sections to be achieved in reinforced concrete that would otherwise require prestressing. Bundling of bars does, however, require some modifications in detailing of lap splices and anchorages with respect to provisions for individual bars.

The bond action of ribbed reinforcing bars generates bursting forces that generate circumferential tensile stresses around the bar and tend to split the surrounding concrete cover.² Unless confinement is high (typically where concrete cover is greater than 5 times the diameter of the lapped bars or where compressive stress is applied perpendicular to the bar axis as at an end support, for example), bond failure of laps and anchorages usually occurs in a splitting mode with formation of longitudinal cover cracks throughout the bond length, leading to eventual spalling of the cover. Bond strength in this mode of failure is limited by the resistance of the section to these bursting forces. Most design codes recognize the importance of the splitting mode of failure through bond strength and detailing provisions linked to minimum cover thickness and the area of secondary reinforcement provided. Some codes also reflect the enhancement in bond obtained in the presence of transverse compressive stress. Code rules for laps and anchorages of individual bars have been validated against an extensive set of physical test data on splices and anchorages of individual bars in which these

parameters vary over a wide range.^{3,4} The data are, however, almost entirely restricted to splices between individual bars, where all bars are spliced at the same cross section.

Although there is a small amount of test data on anchorage of bundled bars,⁵ there appears to be an almost complete absence of test data on lap splices of bars within a bundle. Stressing of a bundle differs markedly between these two situations: in an anchorage, all bars in the bundle are pulled in the same direction, whereas in a splice, pairs of bars are pulled in opposite directions while the remainder are continuous throughout the splice length. Other, more general differences may also exist between laps and anchorages: anchorages at end supports often benefit from transverse compression generated by the support reaction, but lapped splices will invariably be located where transverse stress is negligible. The only study of splices of bundled bars known to the author is reported by Bashandy,⁶ but herein, entire bundles of up to four bars were spliced at the same cross section (giving a total of as many as eight bars in contact within the splice length). Hence, detailing was not representative of normal practice nor compliant with ACI 318-08,⁷ which states that bars are to be spliced individually and that splices within a bundle are not to overlap.

There are several factors that could be expected to enhance the performance of splices of single bars within a bundle when compared with similar splices of individual bars:

1. Clear spacing between bars is increased (for a given section breadth);
2. For a given stirrup diameter and spacing, confinement to each lap within a bundle is increased as splices are staggered; and
3. A proportion of the bars will be continuous where a single bar within the bundle is spliced.

Other factors may have an adverse effect:

4. The perimeter of the bar in direct contact with concrete is reduced.

Further differences may arise as a consequence of staggering splices of individual bars in the bundle:

5. The distribution of bond stress throughout the splice length may alter; and
6. The share of tension force taken by individual bars may alter as a result of differences in stiffness between spliced and continuous bars.

The aims of this investigation are therefore to assess whether the rules in ACI 318-08⁷ for lap joints of bars within a bundle are soundly based and, if appropriate, suggest revisions.

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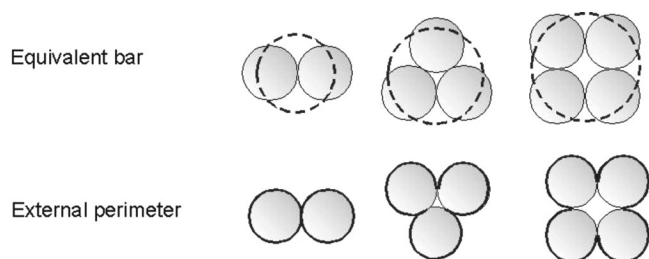
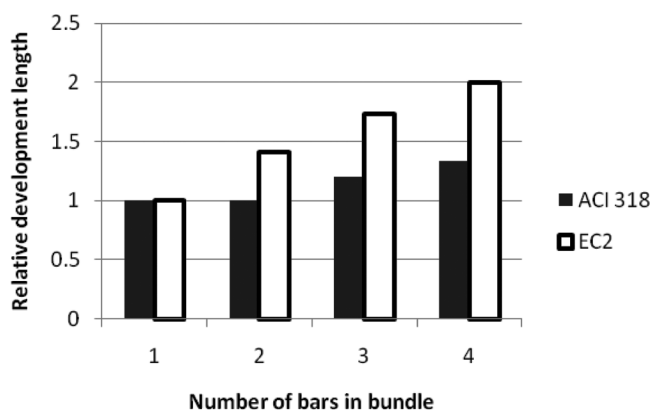
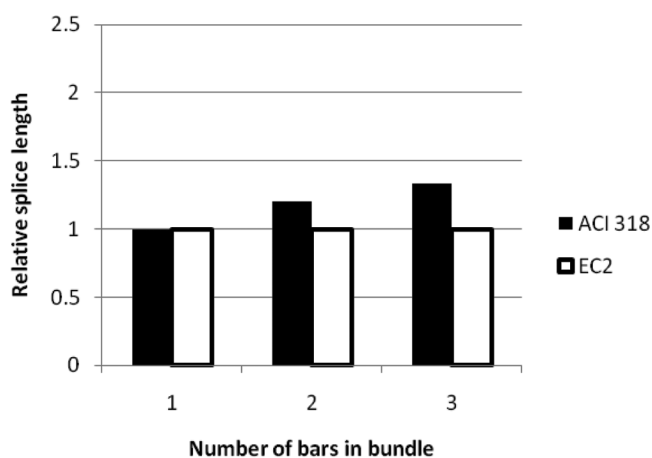


Fig. 1—Equivalent diameter and exposed perimeter of bundles.



(a) Development or anchorage



(b) Lapped splices

Fig. 2—Comparison of ACI 318-08⁷ and EC2⁸ bond lengths for bundles.

RESEARCH SIGNIFICANCE

This paper evaluates the provisions of ACI 318-08⁷ for lap splices of individual bars within a bundle and identifies deficiencies in the rules.

Review of code provisions

Both ACI 318-08⁷ and Eurocode 2 (EC2)⁸ impose a maximum limit of four bars in contact (including within a splice); hence, the maximum bundle within which a bar may

be lap-spliced comprises three bars. ACI 318-08⁷ permits only one bar within a bundle to be spliced at any section. Compared to a lap splice of a pair of single bars, the lap length for an individual bar within a bundle is increased by 20% and 33% for two and three bar bundles, respectively. The increase reflects the reduction in the exposed perimeter of the group relative to that of the same number of bars fixed separately (Fig. 1). Lap-splice length for individual bars within a bundle is, thus, effectively the same as the development length for the entire bundle. In addition, as the equivalent bar diameter is used in place of the actual diameter when calculating the contribution of confinement, the influence of confinement is effectively downgraded and, consequently, the increase in splice length may be somewhat greater in certain circumstances.

The provisions of EC2⁸ are markedly different from those of ACI 318-08.⁷ Where an entire bundle is stopped, anchorage length is determined using an equivalent diameter in which the bundle is replaced by a single notional bar with an area equal to that of the entire bundle. If all bars in the bundle are of the same diameter, the diameter of the equivalent bar d_{bn} is $d_b \sqrt{n_b}$, where d_b is the individual bar diameter and n_b is the number of bars in the bundle. If the equivalent diameter for a bundle of two bars does not exceed 32 mm (No. 10), both may be spliced at the same section. Splice length is based on the equivalent diameter of the pair and splices need not be staggered. Otherwise, only one bar in a bundle of two or three bars (that is, three or four bars, respectively, within the spliced zone) may be spliced at a section and splices must be staggered longitudinally by a distance of 1.3 times the lap length. No increase in splice length is required above that for an individual bar, however.

Figure 2(a) and (b) shows the increase in development and splice lengths required for bundled bars by the two codes over that required for an individual bar. It is assumed that all bars within the bundle are anchored at the same location, but that only one of the bars within the bundle is spliced at a section and splices are staggered longitudinally in accordance with code provisions. The plot takes no account of possible differences in minimum concrete cover or clear spacing between bars as a result of bundling. The plots show that EC2⁸ requires greater increases than ACI 318-08⁷ in development (or anchorage) length with an increasing number of bars in a bundle; for splices of bars within bundles, ACI 318-08⁷ requires an increase, whereas EC2⁸ does not. Thus, the approaches and the consequent bundled splice-length factors in the two codes differ significantly.

The difference in detailing rules for bond of bundled bars between the two codes reflects a difference in the physical concept of bond action. The ACI 318-08⁷ approach treats bond strength as an interfacial shear stress on the bar surface that is constant under any specific confinement condition. As only the external surface of the bundle is considered active in bond (Fig. 1), the force that may be transferred is considered to be reduced if more than two bars are in contact. The concept underpinning EC2⁸ is that splice or anchorage capacity is determined by the available confinement from the surrounding concrete and transverse reinforcement—together with transverse pressure where present—to resist the bursting force generated by bond action. The force to be transferred into a bar is the same whether the bar is part of a bundle or not; consequently, EC2⁸ does not require an increased bond length. The differences between the two documents are therefore not merely an issue of the numer-

ical value of coefficients but reflect significant differences in the underlying concept of behavior.

Recent research by Bashandy⁶ demonstrated that the equivalent bar approach is valid for simultaneous laps of a pair of bars in a bundle (in fact, the investigation went well beyond good detailing practice by simultaneously lapping entire bundles of up to four bars—a practice not permitted in either EC2⁸ or ACI 318-08⁷). However, the author has found no evidence to validate either set of code rules for staggered laps of individual bars within a bundle of two or three bars. This investigation was therefore undertaken to assess the validity of current rules for the dimensioning of lap splices of individual bars within a bundle.

Both codes may require that laps within bundles be staggered. The effect of staggering of laps and its corollary—maintaining continuity of a proportion of bars through a splice zone—is not clear. Both EC2⁸ and ACI 318-08⁷ encourage staggering of laps through reduction factors on lap length, linked with the area of reinforcement provided in relation to that required by calculation in the case of ACI 318-08.⁷ Although it might intuitively be felt that bar continuity through a splice zone would be beneficial, test data are scarce. Such test data are derived from tests in which a proportion of bars was continuous throughout the entire span,^{9,10} whereas in practice, all bars are likely to be lap-spliced but the splices staggered. In some cases, the lap lengths used were short¹⁰ and their consequent weakness may well have presented continuity of a proportion of bars in an unduly favorable light.

The distribution of bond stress over a tension lap length will be affected by the proportion of continuous bars at the splice section. Consider a splice zone situated within a constant-moment zone, stressed within the elastic range, and of sufficient length to allow all bars in the section—whether spliced or not—to be under the same strain at midlength. If all bars are spliced at the same section, the total cross-sectional area of reinforcement within the splice length is double that outside. As the force is divided equally between them, then bar stress, and therefore strain, at midlength of the splice tends toward a value half that outside the splice zone. If only a portion of bars in the section is spliced, the total cross-sectional area of reinforcement within the splice length is less than double that outside; therefore, the strain at the midlength must exceed half of that outside (Eq. (1) and Fig. 3).

$$\epsilon_{ml} = \epsilon_{so} \frac{\Sigma A_{so}}{\Sigma A_{ml}} = \epsilon_{so} \frac{1}{(1 + \rho_1)} \quad (1)$$

where ϵ_{ml} and ϵ_{so} are the bar strains at midlength and outside the long splice, respectively; ΣA_{ml} and ΣA_{so} are the areas of reinforcement within and outside the long splice, respectively; and ρ_1 is the proportion of reinforcement spliced at the section.

While Eq. (1) makes considerable simplifications about load sharing and bar/concrete slip, it does demonstrate that the force to be transferred over the end half of a splice length will tend to be higher when only a portion of the bars is spliced. Splitting bond failure in a long splice is initiated by the peak bond stress near the ends of the splice; hence, the average bond strength over the entire splice length at failure tends to decrease as the proportion of bars spliced increases.

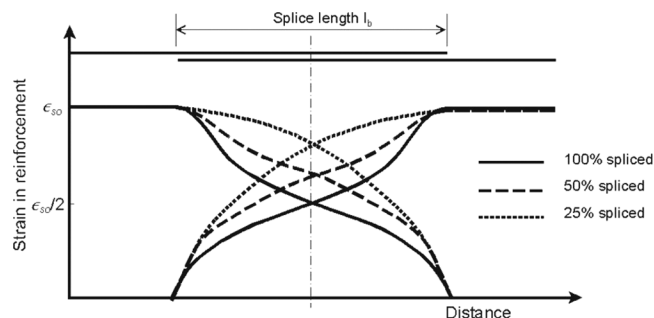


Fig. 3—Influence of proportion of bars lapped at a section on distribution of bar strains through splice length.

The overall stiffness of a splice also varies with the proportion spliced. The overall elongation δ_{lap} of a pair of spliced bars over the splice length is the sum of two components: 1) the elongation of a spliced bar over the splice length; and 2) the combined loaded end slips s_b of the pair of spliced bars (Eq. (2)).

$$\delta_{lap} = \int_0^{l_b} \epsilon_s dx + s_b \quad (2)$$

where ϵ_s is the axial strain in reinforcement at any point; l_b is the splice length; and s_b is the bar slip at the ends of the splice.

The first component on the right-hand side of Eq. (2) is represented by the area under the various curves in Fig. 3, from which it is evident that the proportion of bars spliced at a section will affect splice elongation (that is, will affect the stiffness of the splice). Differences in splice stiffness will affect the balance between the stress carried by continuous and spliced bars.

EXPERIMENTAL PROGRAM

Design

The test program comprised two groups of specimens, each containing five specimens. One group was designed around splices in a two-bar bundle and the other was designed around splices in a three-bar bundle. To exclude the influence of staggering of splice zones from the study, splices were staggered in a consistent manner in both bundle and individual bar splices. Some reference specimens with all bars spliced at the same section were also included, however, as a benchmark against the wider data population. The influence of staggering of laps is being investigated in greater detail in a related study, the initial results from which have already been reported.⁹

The reinforcement layouts for all specimens are shown schematically in Fig. 4, with details of dimensions in Table 1. Splice length was set at 20 times the bar diameter throughout the investigation to ensure that bond failure would precede yield of reinforcement. Each group contained:

1. A pair of replicate bundle splice beams—designation “Type B”—in which each bar within a bundle was lap-spliced with the splices staggered longitudinally. Longitudinal reinforcement in these specimens comprised six 12 mm (0.47 in.) diameter bars, arranged as either three pairs in one group (B2a and B2b) or as two triplets in the other (B3a and B3b). The bundle size refers to the number of bars in contact outside the splice zones; within the splice zones, the two- and three-bar bundle specimens had three and four bars, respectively, in contact. The proportion of bars spliced at a section



Fig. 4—Main reinforcement splice details (not to scale).

in Specimens B2 and B3 was thus 50% and 33%, respectively. Because of the scarcity of tests in which bars within a bundle are spliced and in view of the potential for variations in workmanship causing differences in the compaction of concrete around and between bundled bars, replicate tests were conducted on these specimens. Specimens B2a and B2b were replicate specimens, as were B3a and B3b.

2. One single-bar splice beam—designation “Type S”—was also reinforced with six 12 mm (0.47 in.) diameter bars but with bars arranged and spliced individually. Splices were staggered longitudinally to match the arrangement in the companion Type B bundled bar specimen.

3. One equivalent bar beam—designation “Type E”—containing single bars with a cross-sectional area approximately equal to that of its companion bundled bar specimen. A single 16 mm (0.63 in.) diameter bar was used in place of each two-bar bundle (equivalent diameter of 17.0 mm [0.67 in.]) and a single 20 mm (0.79 in.) bar replaced each three-bar bundle (equivalent diameter of 20.8 mm [0.82 in.]). Section breadth was adjusted to maintain a similar reinforcement ratio in bundle and equivalent bar specimens. Individual splices were staggered in a manner consistent with Type B and E specimens. However, it was not possible to match both the equivalent bar diameter and the proportion of bars lapped at a section. Beam E2 was reinforced with three 16 mm (0.63 in.) bars with three staggered splices (33% spliced at a section), for example, whereas companion Specimens B2a, B2b, and S2 were detailed with two splice zones in which 50% of the longitudinal bars were spliced in each zone.

4. One reference beam—designation “Type R”—using bars of equivalent diameter to that of its companion bundled bar specimen but with all bars lapped at the same section. The purpose of these specimens was to allow splice strengths measured in the tests herein to be benchmarked against the wider database of tests in which splices were not staggered.

All beams contained approximately 1.2% longitudinal reinforcement and minimum covers were 20 or 23 mm (0.78 or 0.91 in.)—equal to or slightly greater than the largest equivalent bar size tested. A modest quantity of secondary reinforcement in the form of closed stirrups was provided in the lap zones of these specimens. The quantity

Table 1—Details of test specimens

Beam reference	Concrete cube strength f_{cu} , MPa	Bar diameter ϕ , mm	Total number of bars	Number of groups	Bars in group	% spliced	Splice length l_o , mm	Section breadth b , mm	Section depth h , mm	Spacings (Fig. 7)		Stirrups	
										$2c_{st}$, mm	$2c_{sb}$, mm	Number per lap zone	Detail (refer to notes)
B2a	46.7	12	6	3	2	50	240	258	241	67	—	1	1
B2b	46.7	12	6	3	2	50	240	258	241	67	—	1	1
S2	46.7	12	6	6	1	50	240	258	260	51	—	1	1
E2	43.1	16	3	3	1	33	320	228	255	—	98	2	2
R2	43.1	16	3	3	1	100	320	226	254	39	—	3	3
B3a	41.2	12	6	2	3	33	240	258	241	158	—	1	1
B3b	41.2	12	6	2	3	33	240	258	241	158	—	1	1
S3	41.2	12	6	6	1	33	240	266	258	95	—	1	1
E3	42.0	20	2	2	1	50	400	224	303	—	161	2	2
R3	43.1	20	2	2	1	100	400	226	270	94	—	3	3

Notes on stirrup detail: 1 is center of each splice zone; 2 is 40 mm (1.57 in.) from both ends of each splice zone; 3 is 40 mm (1.57 in.) from both ends and center of each splice zone; 1 MPa = 145 psi; 1 mm = 0.0394 in.

was kept close to the permitted minimum to reduce uncertainties in the interpretation of the contribution of stirrups to the strength of splices in which only a portion of the bars was spliced at a section. The number of 8 mm (0.31 in.) mild steel stirrups provided to each splice zone is detailed in Table 1. Stirrups were provided at 300 mm (12 in.) centers outside splice zones.

Materials

Longitudinal reinforcement was of Grade 500B in accordance with BS 4449:2005¹¹ (characteristic of 0.2% of proof strength of 500 MPa [72.5 ksi]). Bars had pairs of crescent-shaped ribs on opposite sides of the bar that merge into the core. The relative rib area was not measured on these particular bars but has been found to typically lie in the range of 0.055 to 0.065 from similar production. The concrete cover to longitudinal bars was provided by proprietary spacers. The concrete was of medium workability (Class S2 in accordance with BS EN 206-1:2000¹² with a slump of 60 mm [2.5 in.]) and a maximum aggregate size of 10 mm [0.375 in.], containing a water-reducing admixture and supplied by a local ready mix company. Concrete was compacted by internal vibration and subsequently cured under damp burlap and polyethylene for at least 3 days before stripping and storage in the laboratory until testing. Standard cube control specimens were taken from each batch and tested at the same age as the splice specimens.

Test procedure

Beams were tested in four-point bending (Fig. 5) with the lap zones positioned within the constant-moment zone in all specimens except E2, where the lap zones extended 28 mm (1.1 in.) beyond the point loads. The tension force to be developed in the reinforcement of Specimen E2 would nonetheless have been constant over the entire lap zone when allowance is made for the effect of inclined cracking within the shear span.

Load was monotonically increased to failure over a period of approximately 30 minutes. Load was applied in increments of 10 kN (2.248 kips) with crack development marked at each stage. Loading was continued until residual strength decreased by at least 25% after the peak load was passed. The rate of displacement was increased during this stage. Load and midspan deflection were logged at 2-second intervals throughout the loading sequence.

Test results

The load-deflection response of all beams was close to linear up to peak load. Minor departures were evident at low loads prior to the initiation of flexural cracking, where stiffness was slightly greater, and close to failure, where the response softened slightly. Vertical flexural cracks formed first within the constant-moment zone, followed by slightly inclined flexural cracks within the shear spans. Failure occurred suddenly on formation of a widening flexural crack near one end of a splice zone and longitudinal cracks along longitudinal tension bars over the splice length. Load dropped immediately after the peak was reached in all tests.

Table 2 lists the peak loads and bond strengths for all specimens. The average stress in reinforcement at peak load f_{su} is calculated using the rectangular stress block for concrete given in EC2⁸ with safety factors taken as 1.0. This stress block is effectively identical to that in ACI 318-08⁷ for the concrete strengths used in this investigation. Reinforcement stress is obtained from the maximum applied moment. A quadratic expression is used to determine the tensile force in longitudinal reinforcement, which is then divided by the total area of reinforcement at a section outside the splice zone to obtain an average reinforcement stress at maximum load. Ultimate bond strength f_{bu} is then calculated by Eq. (3) as an average value over the splice length.

$$f_{bu} = \frac{f_{su}}{4 \left(\frac{l_b}{d_b} \right)} \quad (3)$$

where f_{su} is the peak load bar stress; l_b is the splice length; and d_b is the individual bar diameter. The results from replicate bundled splice specimen pairs B2a/b and B3a/b differ

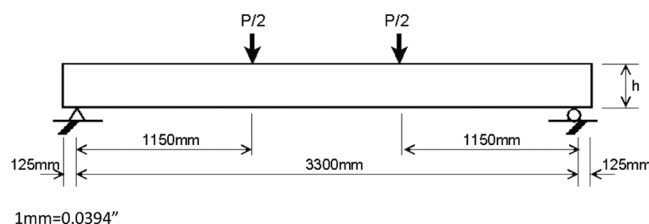


Fig. 5—Load arrangement.

Table 2—Test results

Beam reference	Maximum load, kN	Bond strength		Ductility D_{res}	Bond strength ratio $f_{b,test}/f_{b,calc}$
		Test, Eq. (3) $f_{b,test}$, MPa	Calculated, Eq. (4) $f_{b,calc}$, MPa		
B2a	92.5	5.30	3.45	0.76	1.54
B2b	86.7	5.09	3.46	0.70	1.47
S2	93.5	4.86	3.35	0.43	1.45
E2	76.9	4.66	3.85	0.28	1.21
R2	79.6	4.85	3.03	0.83	1.60
B3a	94.3	5.33	3.97	0.27	1.34
B3b	93.4	5.26	3.99	0.75	1.32
S3	101.3	5.26	3.65	0.20	1.43
E3	83.3	5.22	3.75	0.30	1.30
R3	98.9	5.38	3.17	0.23	1.69

Notes: 1 kN = 0.225 kips; 1 MPa = 145 psi.

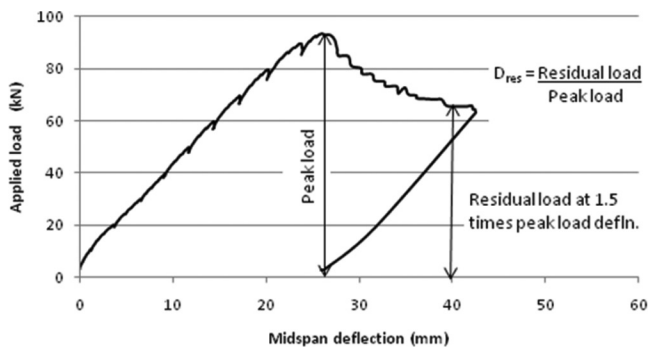
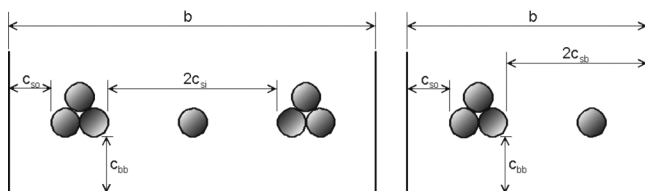


Fig. 6—Typical plot of load versus deflection (Beam B2a) showing calculation of deformability index D_{res} . (Note: 1 kN = 0.225 kips; 1 mm = 0.0394 in.)



$$c_{min} = \min(c_{si} + 6, c_{so}, c_{cb})$$

$$c_{max} = \max(c_{si} + 6, c_{so}) \text{ but } \geq c_{sb}$$

Fig. 7—Definition of cover dimensions.

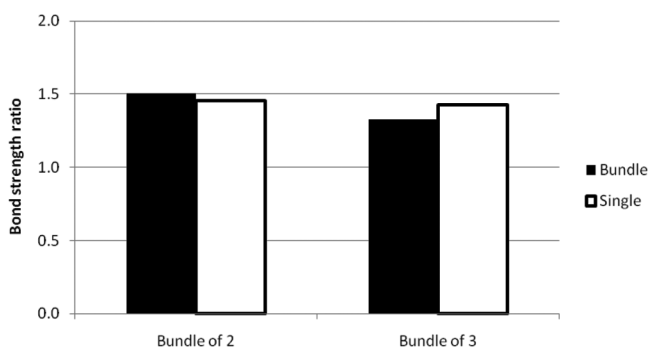


Fig. 8—Influence of bundling bars on bond strength ratio.

by less than 4%—well within the typical scatter of bond strength measurements.

An indication of the brittleness of failure is also given by the quantity D_{res} , calculated as the ratio of residual load at a deflection equal to 1.5 times the peak load deflection to the peak load itself (Fig. 6).

Reference Specimens R2 and R3 were included in the test program to verify that splice strengths measured in the tests herein were consistent with existing “best-fit” semi-empirical expressions proposed by others and hence represent a valid benchmark against which other results reported herein may be compared. These two beams were both reinforced with single bars, all lap-spliced at the same section—the same form as in the majority of specimens used to calibrate such expressions. The strengths measured in Specimens R2 and R3 were 96% and 105%, respectively, of those estimated by the expression proposed by Zuo and Darwin,⁴ for example, and may therefore be considered representative of the larger body of test data.

Bond strengths in a bundle of two or three (“B” specimens) average 7% and 1% higher, respectively, than similar

splices where bars are spliced individually (“S” specimens). The direct comparison of bond strengths presented in Table 2 does not, however, consider differences attributable to bar size or confinement from concrete and stirrups. Minimum concrete cover was essentially constant throughout the program, but clear spacing between splices $2c_{so}$ or the greater side cover $2c_{so}$ (Fig. 7) was greater where fewer bars were spliced at a section. Various empirical and semi-empirical expressions have been proposed to account for the influence of minimum cover, clear spacing between bars, and confining reinforcement.^{3,13} One such expression, adapted by rearranging the design expression proposed by Darwin et al.¹⁴ and subsequently adopted into ACI 318-08,⁷ is given herein as Eq. (4) and is applicable to standard ribbed bars in a bottom-cast situation.

$$f_{b,calc} = \left[0.375 \left(\frac{c_b \omega + K'_{tr}}{d_b} \right) + 12 \omega \frac{d_b}{l_b} \right] f'_c{}^{0.25} \text{ (SI)} \quad (4)$$

$$f_{b,calc} = \left[15.5 \left(\frac{c_b \omega + K'_{tr}}{d_b} \right) + 500 \omega \frac{d_b}{l_b} \right] f'_c{}^{0.25} \text{ (in.-lb)}$$

where $f_{b,calc}$ is the average bond stress over the splice length in MPa (psi); and f'_c is the measured concrete cylinder compressive strength, taken as 0.8 times the cube compressive strength in MPa (psi)

$$c_b = c_{min} + 0.5d_b \quad (5)$$

$$\omega = 0.1 \frac{c_{max}}{c_{min}} + 0.9 \leq 1.25 \quad (6)$$

where c_{max} and c_{min} in mm (in.) are defined in Fig. 7

$$K'_{tr} = 6t_d \Sigma A_{tr} \sqrt{f'_c} / (l_b n) \text{ (SI)} \quad (7)$$

$$K'_{tr} = t_d \Sigma A_{tr} \sqrt{f'_c} / (2l_b n) \text{ (in.-lb)}$$

$$t_d = 0.03d_b + 0.22 \text{ (SI)} \quad (8)$$

$$t_d = 0.78d_b + 0.22 \text{ (in.-lb)}$$

where ΣA_{tr} is the total area of transverse reinforcement within splice length l_b crossing the potential splitting plane in mm² (in.²); and n is the number of bars spliced at the section.

Further analysis of the results is based on the bond strength ratio—the ratio of measured bond strength to that estimated by Eq. (4)—listed in the final column of Table 2.

The influence of bundling of reinforcement is plotted in Fig. 8, in which the bond strength ratios for bundled bars (beams designated “B”) are compared with those for beams with the same reinforcement but positioned and spliced individually (beams designated “S”). The value plotted for bundled laps is the average of two individual tests, while that for the individually spliced bars is a single value. Overall, the difference between bundled and individual strength ratios is 2% and is not significant.

Figure 9 compares the bond strength ratio of bars lap-spliced within a bundle (beams designated “B”) with that of

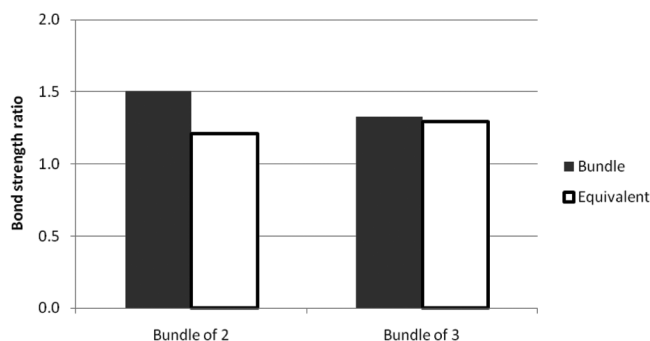


Fig. 9—Bundles and equivalent bars.

their equivalent single-bar (Type E) specimens. The equivalent bar splice was 20% weaker in splices based on a two-bar bundle, while in the three-bar bundle, the equivalent splice was only 2% weaker. These results may appear inconsistent, but this comparison between the bundled bar laps and their companion “equivalent bar” specimens overlooks the difference in the proportion of bars lapped at a section. In beams modeled on the two-bundle arrangement, 50% of the bars were lapped at a section in the bundled bar specimens and 33% were lapped at a section in the equivalent bar specimens. The proportions were reversed in specimens modeled on a three-bar bundle.

Figure 10 plots the bond strength ratio for all specimens tested herein and shows a reduction in the bond strength ratio as the proportion of bars lapped at a section decreases. The bond strength ratio decreased by an average of 20% as the proportion of bars lapped at the section decreased from 100 to 33%. The results for lap splices within bundles are consistent with those for individually lapped bars. A direct comparison between the equivalent and reference specimens (Fig. 11) provides further confirmation that reducing the proportion of bars lapped at a section reduces splice strength. The only difference between the equivalent and reference splices was the proportion of bars lapped at a section. Equivalent splices in which splices were staggered were 25% weaker in both groups.

Splice strength decreased immediately after peak load in all tests. No influence of bundle size on brittleness of failure, as measured by the deformability index D_{res} , is apparent (Fig. 12), but there is a marked correlation with the proportion of bars spliced at a section (Fig. 13). The deformability index D_{res} decreased from approximately 0.75 where 33% of bars were spliced at a section to averages of 0.35 and 0.25, where 50% and 100% of bars, respectively, were spliced at a section. Even in the least brittle configurations, where one-third of the bars were spliced at a section, residual bond strength still dropped by 20 to 30% shortly after peak load. The change is similar for individual lapped bars and for bars within a bundle. Metelli et al.⁹ similarly observed less brittle behavior, where a proportion of reinforcement is continuous through a lapped splice.

COMPARISON WITH ACI 318-08⁷ PROVISIONS

The original aim of this investigation was to determine whether splice length of bars within a bundle should be increased relative to that of individually spliced bars. The results plotted in Fig. 8 show that bond strength is not reduced in the bundled detail. Consequently, the increased splice lengths in ACI 318-08⁷ for laps of bars forming part of a bundle do not appear to be justified. The approach of

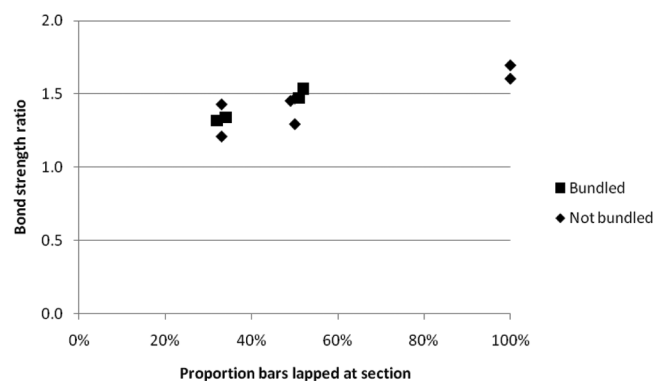


Fig. 10—Influence of proportion of bars lap spliced at section on bond strength ratio.

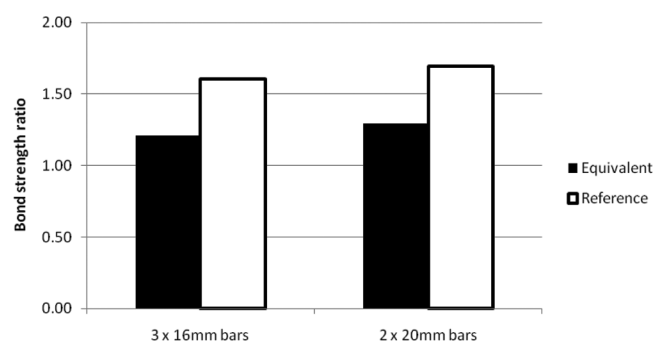


Fig. 11—Influence of staggering of laps on bond strength ratio. (Note: 1 mm = 0.0394 in.)

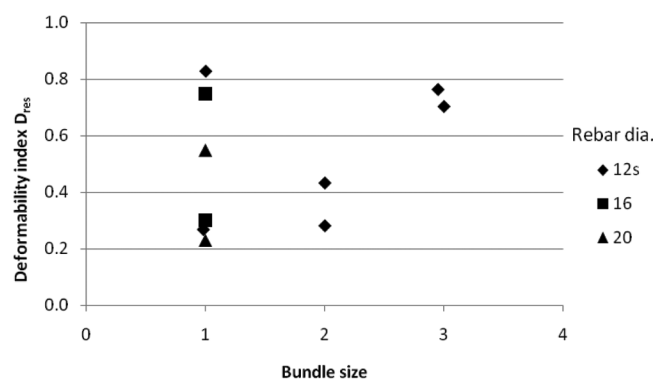


Fig. 12—Influence of bundle size on deformability.

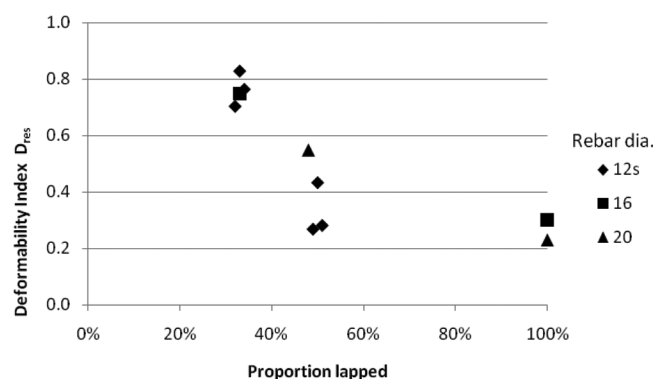


Fig. 13—Influence of proportion of bars lapped at a section on deformability.

EC2⁸ to the design of laps in bundles that does not require increases for bars in bundles and in which confinement factors are based on the individual bar size provides a more consistent level of safety than the ACI 318-08⁷ approach.

These results indicate that the ability of a lap splice to transfer force is determined more by the resistance to splitting than by a notional shear stress over the exposed perimeter of the bar. It is possible that in conditions of high cover, confining reinforcement, or transverse pressure—where a pullout failure occurs instead of a splitting failure—that this conclusion might be inappropriate. The splitting mode of failure is the weaker and more likely mode in structurally significant members; consequently, design rules for lap splices are based on this mode.

What does emerge from this study, however, is that lap splices of individual bars in bundles may be weaker than individual lap splices because splice strength decreases with the proportion of the bars spliced at a section. This trend is not confined to bundled bars but is also evident in individual bar splices (Fig. 10 and 11). This trend is contrary to the provisions of both ACI 318-08⁷ and EC2,⁸ where staggering of lap splices and retaining continuity of a portion of bars through a splice zone is considered beneficial. EC2⁸ permits splice length to be reduced where only a portion of the bars is spliced at a section. If only one-third of the bars are spliced at a section, a reduction in bond length of 23% is permitted. ACI 318-08⁷ effectively permits a similar reduction in splice length for Class A splices. Splices are classified as Class A where the area of reinforcement provided is: 1) at least double that required by analysis; and 2) no more than 50% of bars are lapped at a section. Based on the admittedly limited number of specimens in this investigation, it could reasonably be concluded that an *increase* of this amount would be justified.

Various factors that might influence the performance of splices of single bars within a bundle relative to similar splices of individual bars were listed in the Introduction of this paper. Variations in confinement from cover and confining reinforcement have been taken into account in the analysis, and the reduction in exposed bar perimeter does not appear to influence the results. It can therefore be inferred that the reduction in splice strength is related to the distribution of bond stress along the splice length and differences in the share of load between spliced and continuous bars (Fig. 3). This tentative conclusion must be treated with caution, however, as in these tests, the stagger between lap zones was less than specified in either ACI 318-08⁷ or EC2⁸ due to physical constraints on the dimensions of test specimens in this investigation. Further investigation on splices staggered in accordance with code requirements is therefore required. In practice, bundling of reinforcement is employed only with large-diameter bars and further tests should be designed accordingly.

Strength is not the only aspect of structural performance that needs to be considered, and structural robustness will be strongly influenced by the brittleness or deformability of splice behavior. The results show an increase in post-peak residual strength where only a portion of the bars are spliced (Fig. 13). The gain in structural robustness as a consequence of reduced brittleness is difficult to evaluate and will depend on the structural arrangement considered, particularly on the degree of indeterminacy. Further detailed work is required to resolve this issue, but in the meantime, it would seem advisable at the very least to remove the reductions in splice

length currently permitted for continuity of bars through a splice zone.

SUMMARY AND CONCLUSIONS

This study set out to determine whether bond strength is reduced where a single bar within a bundle of two or three is lap-spliced. Within the scope of the investigation, it is concluded that:

1. Bond strength is not reduced where an individual bar within a pair or bundle of three bars is lap-spliced and appropriate allowance is made for differences in confinement and the proportion of bars spliced at a section.

2. The results suggest that the strength of a lapped splice is controlled by resistance to the bursting forces generated by bond action rather than a notional shear resistance on the exposed portion of the bar surface.

3. Splicing only a portion of bars at a section reduced splice strength whether or not spliced bars formed part of a bundle. Consequently, the reductions in splice length currently permitted for continuity of bars through a splice zone may be unsound, and further investigation as a matter of priority is merited.

4. Less-brittle failures were observed where lap joints were staggered longitudinally over three zones instead of one or two, regardless of whether the lap was between individual bars or of an individual bar in a bundle. Failure could not be classified as ductile, however.

5. On the evidence of this study, the requirement of ACI 318-08⁷ to increase the development length for bars spliced within a bundle over that for an individual bar appears to be unwarranted. However, as this increase compensates for an observed reduction in strength believed to be attributable to staggering of splices, no changes in the ACI 318-08⁷ provisions for splices of bars in bundles should be introduced until the influence of staggering on splice resistance is better understood.

6. It is desirable that the further work proposed previously use larger-diameter bars more representative of circumstances in which lapping of bundled bars may be required in practice.

ACKNOWLEDGMENTS

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NOTATION

c_{max}	=	secondary cover dimension (refer to Fig. 7)
c_{min}	=	minimum concrete dimension (refer to Fig. 7)
d_b	=	bar diameter
$f_{b,calc}$	=	average bond stress over splice length calculated according to expression of Darwin et al. ¹⁴
f_{bu}	=	bond stress at peak load from test
f'_c	=	concrete cylinder compressive strength
f_{su}	=	bar stress at peak load from test
K_{tr}	=	parameter representing amount of transverse reinforcement contributing to bond resistance
l_b	=	splice length
n	=	number of bars spliced at section
n_b	=	number of bars in bundle
s_b	=	bar slip at ends of splice
t_d	=	dimensionless parameter representing influence of bar diameter
ϵ_s	=	axial strain in reinforcement; ϵ_{ml} and ϵ_{so} are strains at midlength and outside splice
ρ_l	=	proportion of reinforcement spliced at section
$\Sigma A_{ml}, \Sigma A_{so}$	=	areas of reinforcement within and outside long splice, respectively
ΣA_{tr}	=	total area of transverse reinforcement within splice length l_b crossing potential splitting plane

REFERENCES

1. *Standard Method of Detailing Structural Concrete: A Manual for Best Practice*, third edition, Institution of Structural Engineers, London, UK, 2006, 188 pp.
2. *fib* Bulletin 10, "Bond of Reinforcement in Concrete: State-of-Art Report," *fib*, Lausanne, Switzerland, Aug. 2000, 434 pp.
3. Orangun, C. O.; Jirsa, J. O.; and Breen, J. E., "A Reevaluation of Test Data on Development Length and Splices," *ACI JOURNAL*, *Proceedings* V. 74, No. 3, Mar. 1977, pp. 114-122.
4. Zuo, J., and Darwin, D., "Splice Strength of Conventional and High Relative Rib Area Bars in Normal and High-Strength Concrete," *ACI Structural Journal*, V. 97, No. 4, July-Aug. 2000, pp. 630-641.
5. Jirsa, J. O.; Chen, W.; Grant, D. B.; and Elizondo, R., "Development of Bundled Reinforcing Steel," *Report 0-1363-2F*, Center for Transportation Research, the University of Texas at Austin, Austin, TX, 1995, 103 pp.
6. Bashandy, T. R., "Evaluation of Bundled Bar Lap Splices," *ACI Structural Journal*, V. 106, No. 2, Mar.-Apr. 2009, pp. 215-221.
7. ACI Committee 318, "Building Code Requirements for Structural Concrete (ACI 318-08) and Commentary," American Concrete Institute, Farmington Hills, MI, 2008, 473 pp.
8. BS EN 1992-1-1:2004, "Eurocode 2: Design of Concrete Structures—Part 1-1: General Rules and Rules for Buildings," British Standards Institution, London, UK, 2004, 225 pp.
9. Metelli, G.; Cairns, J.; and Plizzari, G., "Influence of Bar Continuity on Behaviour of Lapped Splices," *Proceedings of the 2010 fib Congress and PCI Convention Bridge Conference*, Washington, DC, June 2010, pp. 2904-2915.
10. Magnusson, J., "Bond and Anchorage of Ribbed Bars in High-Strength Concrete," PhD thesis, Chalmers University, Göteborg, Sweden, 1997, 234 pp.
11. BS 4449:2005+A2:2009, "Steel for the Reinforcement of Concrete. Weldable Reinforcing Steel. Bar, Coil and Decoiled Product. Specification," British Standards Institution, London, UK, 2009, 34 pp.
12. BS EN 206-1:2000, "Concrete. Specification, Performance, Production and Conformity," British Standards Institution, London, UK, 2001, 74 pp.
13. Canbay, E., and Frosch, R. J., "Bond Strength of Lap-Spliced Bars," *ACI Structural Journal*, V. 102, No. 4, July-Aug. 2005, pp. 605-614.
14. Darwin, D.; Lutz, L. A.; and Zuo, J., "Recommended Provisions and Commentary on Development and Lap Splice Lengths for Deformed Reinforcing Bars in Tension," *ACI Structural Journal*, V. 102, No. 6, Nov.-Dec. 2005, pp. 892-900.

NOTES:
